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Measurement of normal and pathological mandibular and temporomandibular joint kinematics: A systematic review

Woodford, Sarah C ; Robinson, Dale L ; Mehl, Albert ; Lee, Peter V S ; Ackland, David C

Abstract: Motion of the mandible and temporomandibular joint (TMJ) plays a pivotal role in the function of the dentition and associated hard and soft tissue structures, and facilitates mastication, oral communication and access to respiratory and digestive systems. Quantification of TMJ kinematics is clinically relevant in cases of prosthetic rehabilitations, TMJ disorders, osteoarthritis, trauma, tumour resection and congenital abnormalities, which are known to directly influence mandibular motion and loading. The objective of this systematic review was to critically investigate published literature on historic and contemporary measurement modalities used to quantify in vivo mandibular and TMJ kinematics in six degrees of freedom. The electronic databases of Scopus, Web of Science, Medline, Embase and Central were searched and 109 relevant articles identified. Publication quality was documented using a modified Downs and Black checklist. Axiography and ultrasonic tracking are commonly employed in the clinical setting due to their simplicity and capacity to rapidly acquire low-fidelity mandibular motion data. Magnetic and optoelectronic tracking have been used in combination with dental splints to produce higher accuracy measurements while minimising skin motion artefact, but at the expense of setup time and cost. Four-dimensional computed tomography provides direct 3D measurement of mandibular and TMJ motion while circumventing skin motion artefact entirely, but employs ionising radiation, is restricted to low sampling frequencies, and requires time-consuming image processing. Recent advances in magnetic tracking using miniature sensors adhered to the teeth in combination with intraoral scanning may facilitate rapid and high precision mandibular kinematics measurement in the clinical setting. The findings of this review will guide selection and application of mandibular and TMJ kinematic measurement for both clinical and research applications.

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MEASUREMENT OF THREE-DIMENSIONAL MANDIBLE AND TEMPOROMANDIBULAR JOINT KINEMATICS: A SYSTEMATIC REVIEW

Sarah C. Woodford[1], Dale L. Robinson[1], Albert Mehl[2], Peter Lee[1], David C. Ackland[1]

[1]Department of Biomedical Engineering, University of Melbourne,
Parkville, Victoria 3010, AUSTRALIA
[2]Centre of Dental Medicine, University of Zürich,
Zürich, Switzerland

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Address for correspondence:
David C. Ackland
Department of Biomedical Engineering
University of Melbourne
Parkville, Victoria 3010, AUSTRALIA
Phone: +613 8344 0405
Fax: +613 9347 8784
Email: dackland@unimelb.edu.au

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ABSTRACT

Temporomandibular joint (TMJ) and mandibular motion plays a pivotal role in the function of the dentition and associated hard and soft tissue structures, and facilitates mastication and oral communication. Quantification of mandibular kinematics is clinically relevant in cases of TMJ disorders such as osteoarthritis, TMJ arthroplasty, trauma, tumour resection and congenital abnormalities. The objective of this systematic review was to critically investigate published literature on historic and contemporary measurement modalities used to quantify three-dimensional mandibular and TMJ kinematics *in vivo*. Electronic databases Scopus, Web of Science and Medline were searched, and sixty relevant articles identified. Measurement techniques were assessed for data precision, accuracy, reliability and practicality in the clinical and research settings, and publication quality documented using a modified Downs and Black checklist. Axiography and ultrasonic tracking are simple and fast to implement, but produce low-fidelity mandible motion. Magnetic and optoelectronic tracking have been used in combination with dental splints to produce higher measurement accuracy while minimising skin motion artefact, but at the expense of setup time and cost. Four-dimensional Computed Tomography provides direct 3D measurements of mandible and TMJ motion while circumventing skin motion, but employs ionising radiation, is restricted to low sampling frequencies and requires time-consuming image processing. Recent advances in magnetic tracking using miniature sensors adhered to the teeth in combination with intraoral scanning facilitates rapid and high precision mandibular kinematics measurement in the clinical setting. The findings of this review will guide application of mandibular and TMJ kinematic measurement in both the clinic and research settings.

INTRODUCTION

The temporomandibular joint (TMJ) is a bilateral synovial joint between the skull and the mandible comprising the glenoid fossa of the temporal bone, the condylar head of the mandible, and the articular cartilage and disc. Motion of the TMJ is essential for normal mandibular function and maintaining quality of life, providing the mechanism for biting, chewing, swallowing and speech. The American Academy of Orofacial Pain estimates that 75% of the U.S. population experiences temporomandibular disorders that directly impact mandibular motion at some point in their life, with 5 to 10% of those requiring surgical or non-surgical treatment (Gatchel et al., 2006). Loss of TMJ function and mandibular pain is associated with reduced diet and social dysfunction (Reisine and Weber, 1989), and has been directly attributed to annual costs to the US healthcare system of over $2 billion (Gatchel et al., 2006).

TMJ motion measurement plays an important role in medicine by facilitating development of tests to screen for temporomandibular dysfunction (Sadat-Khonsari et al., 2003a), for evaluating mandibular function, outcomes of TMJ reconstructive and total joint replacement surgery (Alsawaf et al., 1993; Sforza et al., 2011; Ugolini et al., 2017), therapeutic measures such as occlusal splints (Ettlin et al., 2008; Vilanova et al., 2014), and for assessing the functional performance of dental implants and prosthetics (Baltali et al., 2008a; Leiggener et al., 2012; Wojczynska et al., 2019). Mandibular kinematics has also been used to quantify the effects of gender on mandibular function and disease progression (Buschang et al., 2000; Ferrario et al., 2005; Lewis et al., 2001; Mapelli et al., 2009), as well as age-related changes in mandibular behaviour (Baqaien et al., 2007; Gibbs et al., 1982; Martin et al., 2000).

Mandibular motion measurement techniques can be broadly classified into four categories: (i) mechanical linkage systems, (ii) magnetic tracking systems, (iii) video motion analysis, and (iv) radiographic tracking. Mechanical linkage systems include axiography, the Case Gnathic Replicator and ultrasonic tracking, and involve rigidly fixing instrumented face-bows to the teeth from which mandibular motion can be directly measured. Magnetic tracking systems have been adopted to acquire kinematics data from electromagnetic sensors mounted to anatomical landmarks such as dental structures. Similarly, video motion analysis methods such as cinematography and optoelectronic tracking employ stereophotogrammetry to directly measure mandibular motion from the position of markers attached to the face, or adhered to the mandibular or maxillary teeth. In contrast, radiographic tracking can directly measure bone motion and include video x-ray fluoroscopy and 4D computed tomography (4D-CT).

The aim of this systematic review was to assess strategies for quantifying three-dimensional (3D) mandible and TMJ motion and report their data precision, accuracy, reliability and practicality. The outcomes of this study may be useful in guiding motion measurement experiments for the clinic and research setting.

MATERIALS AND METHODS

Database Search Strategy

A literature search was conducted to identify previously published articles that describe the measurement of 3D mandibular or TMJ kinematics. The study was compliant with the recommended Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009). Articles were identified through a systematic search of the following three databases: (1) Scopus, (2) Web of Science and (3) Medline, via Ovid. These databases were searched for entries published in English with no date restrictions. Keywords included "temporomandibular joint", "kinematic*", "biomechanic*", "dynamic*", "jaw motion" and "motion analysis".

Selection Criteria

After removing duplicates from the search results, all titles and abstracts were assessed to determine whether they fulfil the inclusion criterion. To be included in this review, studies were required to meet the following criteria: (i) focused on the native, pathological or surgically altered TMJ, or mandible (jaw) and (ii) reported dynamic 3D kinematics of the mandible or TMJ. Exclusion criteria included (i) animal studies, and (ii) studies of robotic mouth actuators. The references of all full text articles were manually checked for relevant titles to be included in the review.

Article Quality Assessment

The quality of all included studies was evaluated using a customised quality assessment tool which included principles from the STROBE statement (Elm et al., 2007), the Downs and Black checklist (Downs and Black, 1998), and established reliability and feasibility appraisal tools (Crowe and Sheppard, 2011). Quality evaluation guidelines for systematic reviews covering broadly similar themes were also consulted (Hart et al., 2016; Peters et al., 2010; Pourahmadi et al., 2019).

The assessment tool was developed using a scored checklist of quality assessment questions (Table 1). Each question was attributed a score of 2, 1 or 0 based on whether the question in a given paper was clearly addressed, partially addressed or not addressed, respectively. Quality scores were collated and their mean and range calculated. High methodological quality was defined as a score of ≥ 20 (with a maximum 22), moderate quality was defined as a score of > 14 and < 20, and low quality was defined as a score of ≤ 14. Scores were cross-checked by two independent reviewers (SCW and DCA), and discussion between reviewers used to resolve any discrepancies in score.

Data Extraction

In addition to methodological quality, four categories of data were extracted from each identified study. The extracted data include study population, inclusion of subject-specific anatomic data, measurement technique and reported kinematic parameters (Tables 2 and 3).

RESULTS

Search Strategy and Methodological Quality

The initial literature search identified 3,918 titles, 2,040 of which remained after the removal of duplicates. After screening titles and abstracts, 99 studies were found to be potentially eligible, with 60 titles subsequently selected for consideration after verification of inclusion and exclusion criteria (Figure 1). An additional 9 studies were identified and included in the review by searching the references of included articles. The methodological quality scores ranged from 12 to 22, with an average score of 17. There were 12 studies of high quality, 37 studies of moderate quality and 11 studies of low quality (Figure 2).

MECHANICAL LINKAGE SYSTEMS

Case Gnathic Replicator

The Case Gnathic Replicator, which was first developed in 1969, was one of the earliest strategies for calculating 3D mandible kinematics. It comprises six incremental linear displacement transducers mounted between a maxillary face-bow and a mandibular face-bow (

3). The face-bows are attached to the mandible and maxilla via occlusal clutches, which are typically cemented to the surfaces of the teeth. The transducers are used to record relative motion between the face-bows onto magnetic tapes, which can then be played back using a computer, or used to operate casts which replicate the movements of the mandible at reduced speeds (Alexander et al., 1984; Gibbs et al., 1973). The mandibular face-bow is specifically designed to be lightweight, approximately 60 g (Alexander et al., 1984), to avoid interfering with normal mandibular function, however the device is still considered unwieldy, and measurement is time-consuming with extensive calibration required (Piancino and Kyrkanides, 2016). Two studies, one of moderate and one of high methodological quality, employed the Case Gnathic Replicator to measure condylar and incisor trajectories. These data were used to drive dental articulators and assess the effect of tooth contact on TMJ pain (Coffey et al., 1989; Gibbs et al., 1971). One study of moderate quality reported the measurement error to be less than 0.13 mm (Gibbs et al., 1971).

Axiography

Contemporary axiographs can be either mechanical or electromechanical and consist of a double face-bow attached to the participant via occlusal clutches or to the head. The mandibular face-bow is equipped with two styli which trace mandibular movement onto two flaps positioned over the condylar region of the maxillary face-bow (Figure 4). Axiography is commonly used to measure condylar trajectories and Bennett angles (Alsawaf et al., 1993; Hüe, 2011; Kucukkeles et al., 2005; Sadat-Khonsari et al., 2003b; Theusner et al., 1993), and has been employed clinically for diagnostic purposes (Wagner et al., 2003) and for evaluating both intra- and post-operative mandibular function (Ewers et al., 2005; Landes and Sterz, 2003). It is considered a rudimentary measurement system that is inexpensive and can be rapidly setup and deployed, with commercially available products such as the Freecorder®BlueFox now readily available. One study of moderate quality assessed the measurement error of electromechanical axiographs (Sadat-Khonsari et al., 2003a). By mounting the lower face-bow to an X/Y measuring table equipped with micrometre screws to control movement, the recorded displacement was compared to the actual movement of the face-bow. The study reported errors of 0.07 mm per 5 mm travelled in the sagittal plane, and 0.57 mm per 5 mm travelled in the transversal plane, primarily a result of vibration of the face-bow and errors in styli placement. Additionally, the weight of the face-bows, which has been measured at 96 g (Schierz et al., 2014), may ultimately restrict normal dynamic mandibular motion and result in premature fatigue (Kenworthy et al., 1997).

Ultrasonic tracking

Ultrasonic technology has been adapted to measure motion of the mandible by embedding ultrasonic emitters in a face-bow rigidly attached to a subject's mandibular teeth, and ultrasonic receivers positioned in a carrier attached to their head. In this manner, the real-time latency periods of sequentially transmitted ultrasonic pulses between these carriers can be recorded, and the relative motion of the mandible calculated (

Figure 5

5). Four moderate quality studies and four low quality studies employ ultrasonic tracking to quantify dynamic condylar trajectories (Kiseri et al., 2018; Ko et al., 2015; Linsen et al., 2016; Morneburg and Pröschel, 1998; Wang et al., 2009) and TMJ anatomy (Baqaien et al., 2007; Ratzmann et al., 2007) (Table 2). The face-bows, which each weigh 25 g (Baqaien et al., 2007), are quick and easy to mount, giving this technology the advantage of rapid deployment, and application in large cohort studies (Baqaien et al., 2007; Kordaß et al., 2014). Ultrasonic tracking provides an extraoral measure of condylar inclination angles and is often considered a source of 'gold standard' input data to drive dental articulators (Ratzmann et al., 2007). The measurement accuracy of an ultrasonic tracking system was evaluated by mounting the lower face-bow on a micrometre table to control its movement (Hugger et al., 2001). This study reported that for movement paths of up to 20 mm, the mean errors were found to be 0.1 mm in the transversal direction, 0.13 mm in the sagittal direction and 0.17 mm in the vertical direction. Since condylar movement involves both rotation and translation, implementation of a singular condylar reference point may not be adequate for quantifying six degrees-of-freedom TMJ motion (Peck et al., 1999, 1997).

MAGNETIC TRACKING SYSTEMS

Magnetic tracking

Magnetic tracking systems calculate the position and orientation of a point in space using a calibrated sensor that records change in current within a magnetic field. This technique has been well established in biomechanical studies of the spine, shoulder, knee and foot (Hill et al., 2007; Johnson and Anderson, 1990; Russell et al., 1993; Woodburn et al., 1999) and has gained popularity due to the portability and low cost of the hardware. In the research setting, magnetic sensors 22.6 × 12.7 × 11.4 mm in size have been either adhered directly to the teeth using dental adhesive or attached to custom dental splints worn by the participant (Baltali et al., 2008b) (Figure 6). To evaluate TMJ kinematics, the motion tracking data may be registered to bony anatomy using CT scans and custom dental splints with captive radio-opaque beads. However, this application exposes participants to ionising radiation, and dental splints are known to interfere with occlusion, limiting the complete intercuspation by approximately 1 to 2 mm (Baltali et al., 2008b). Magnetic tracking is sensitive to the presence of nearby metal materials, and test subjects must sit on a non-ferrous chair away from metal objects to avoid measurement distortion and errors. Magnetic tracking has been used to measure condylar and incisal trajectories, define the location of the mandibular helical axis, and quantify the effects of partial TMJ reconstruction surgery on mandibular kinematics (Baltali et al., 2008b, 2008a; Keller et al., 2012). One study of high methodological quality used a high precision calibration device to show magnetic tracking sensor measurement errors to be 0.03 ± 0.13 mm (mean ± SD) for linear distances and 0.36 ± 0.44 mm for curvilinear pathways (Baltali et al., 2008b).

Magnetic tracking has advanced in recent years through the development of miniaturized magnetic sensors, 10 × 5 × 5 mm in size attached directly to the teeth with dental cement. These sensors can be quickly attached and removed, do not interfere with dental occlusion during biting, and have sampling frequencies of up to 120 Hz (Baeyens et al., 2013). Sensor data can be registered to bone embedded coordinate systems by digitising bony or dental landmarks using a stylus sensor (Baeyens et al., 2013), or to 3D scans of the dental arch using intra-oral scanners, thus providing dynamic measurements of kinematics for the maxillary and mandibular teeth and the associated TMJ’s, without the need for CT scanning.

VIDEO MOTION ANALYSIS

Optoelectronic tracking

Optoelectronic tracking involves measurement of the 3D positions of markers rigidly attached to the mandible and the maxilla. Optoelectronic markers emit infrared or near-infrared light (active markers) or reflect it (passive retro-reflective markers), while marker positions recorded by two or more cameras are used to compute 3D marker trajectories (Figure 7). To measure mandibular motion, markers are typically attached to a lightweight frame which is rigidly attached to the teeth via subject-specific dental splints, or via adhesion directly to the teeth. In addition to these methods, fixation to the head has been performed using eyeglasses (Gallo et al., 1997), headbands (Ostry et al., 1997) and reference caps (Leader et al., 2003). The key advantages of this approach are that markers can be positioned on mandibular and skull landmarks in order to define anatomical coordinate systems used for evaluating kinematics, and motion data can be recorded at high speeds non-invasively. This technology has been used extensively in biomechanics laboratories to study human gait (Caldas et al., 2017) and joint kinematics (Hanley and Tucker, 2018; Murphy et al., 2006; Small et al., 1996), but can be costly and time consuming to setup and calibrate, and requires a dedicated laboratory space to accommodate the cameras, which is impractical in most clinical settings.

TMJ kinematics has been quantified using optoelectronic systems by registering mandibular motion recordings from marker trajectories to the 3D geometry of the mandible, obtained by digitally reconstructing MRI or CT scans. This technique, first described in 1994 and often referred to as Dynamic Stereometry (Krebs et al., 1994), involves registering optoelectronic kinematic data to bone-fixed co-ordinate systems defined from the location of non-collinear spheres measured using CT or MRI. Imaging is typically performed with the patient biting on a custom-made occlusal splint attached to a frame carrying the active or passive markers, facilitating subsequent coordinate system transformation between the optoelectronic system and the bone-fixed coordinate system.

Optoelectronic tracking systems have been used to evaluate gender-specific mandibular kinematics (Lewis et al., 2001), assess outcomes of orthognathic surgery (Sforza et al., 2010; Ugolini et al., 2017), and quantify the effects of occlusal splint therapy on mandibular kinematics (Ettlin et al., 2008). Optoelectronic tracking systems have been employed in 10 high quality studies, 22 moderate quality studies and 5 low quality studies to measure condylar trajectories and mandibular motion during mandibular border movements (Buschang et al., 2001; Coutant et al., 2008; Gallo et al., 1997; Kim et al., 2010; Leader et al., 2003; Lemoine et al., 2005; Lewis et al., 2001; Mapelli et al., 2016, 2009; Naeije, 2002; Sforza et al., 2011, 2010; Siegler et al., 1991; Slater et al., 1999; Visscher et al., 2000; Yatabe et al., 1997, 1995), mastication (Gallo et al., 2006, 2000; Naeije and Hofman, 2003; Siegler et al., 1991) and speech (Ostry et al., 1997) (Table 3). Additionally, dynamic stereometry has been used to study intra-articular joint space (Chang et al., 2015; Ettlin et al., 2008; Fushima et al., 2003; Gallo et al., 2008; Krebs et al., 1995; Terajima et al., 2008; Yashiro et al., 2015b, 2015a) and intra-articular stress fields during mandibular opening and closing movements (Zaugg et al., 2012).

One study of high methodological quality reported a measurement error of 0.11 ± 0.08 mm in calculation of linear distances using optoelectronic tracking (Fushima et al., 2003), which was primarily a result of warping within the rigid marker frames, poor fixation between the marker frames and the mandible (Otake et al., 2006), and identification of the centre of active

LED markers (Airoldi et al., 1994). The major limitation of most optoelectronic kinematic measurement systems is that of the markers, which are attached directly to the skin, moving relative to the underlying bone resulting in skin motion artefact. This can produce mandible position measurement errors of up to 3.27 mm during mandibular opening and closing movements (Chen et al., 2011). Skin-motion artefact can be overcome by using dental splints attached directly to the teeth and by incorporating medical imaging data to improve registration of anatomical landmarks to measured marker trajectories; however, this increases the complexity, time and expense of the motion analysis.

3D scanning

3D scanning is a non-invasive technology that digitises the shape, texture and colour of an object, ultimately producing a 3D point cloud of the surface topology. By attaching adhesive markers to the surfaces of the mandibular and maxillary incisors, and inserting a lip and check retractor to ensure consistent visibility of the markers, their positions may be tracked during mandibular movement using a structured light 3D scanner at a framerate of up to 50 frames per second (Figure 8). A previous study has registered this motion data to 3D cone-beam CT scans (CBCT) to evaluate condylar trajectories during mandibular border movements (Kwon et al., 2019). Alignment of kinematic data from the 3D scan to the CBCT models is achieved via image registration software. This method of mandibular kinematics measurement may be applicable to the clinic, since it requires only the placement of a retractor and small adhesive markers, and is fast and low cost (Kwon et al., 2019). By attaching small markers directly to the teeth, skin motion artefact and unintended loading of the mandible can be mitigated; however, it may restrict natural mandibular motion, while CBCT registration greatly increases data processing time and exposes participants to ionising radiation. One study of moderate quality showed that 3D scanning can be used to quantify the position of a circular marker with a precision of 4.1 - 6.9 μm (Kwon et al., 2019).

RADIOGRAPHIC TRACKING

Video x-ray fluoroscopy

Single plane video x-ray fluoroscopy employs radiography to calculate bone and joint motion, achieved by registering the position of the 3D geometry of the skull and the mandible reconstructed from CT scans to 2D dynamic motion from video x-ray fluoroscopy recordings (Figure 9). Two studies of moderate quality (Chen et al., 2013a, 2013b) and one study of low quality (Yamazaki et al., 2014) employed single-plane video x-ray fluoroscopy to evaluate rigid body motion, including condylar rotations and translations of the normal functioning mandible during mouth opening and mastication. Pose-estimation was achieved by minimising a weighted edge-matching score calculated when aligning the reconstructed 3D mandible derived from CT scans to the fluoroscopic images (Chen et al., 2013b, 2013a), or by tracking the position of radio-opaque tantalum beads in customized mouthpieces worn by the participants (Yamazaki et al., 2014).

Video x-ray fluoroscopy is known to overcome skin-motion artefact by producing direct measures of mandible motion relative to the maxilla. One study of moderate quality found video x-ray fluoroscopy to have motion measurement errors of 0.2 ± 0.2 mm for in-plane translations, 1.0 ± 1.4 mm for out of plane translations, and 0.2 ± 0.7° for rotations during mouth opening and mastication using single-plane fluoroscopy (Chen et al., 2013a). Out-of-plane errors can be reduced by a factor of 10 using bi-plane fluoroscopy; however, this comes at the expense of greater radiation dosage, additional image processing time, and a more significant initial expense of equipment (Tersi et al., 2013). At present, bi-plane fluoroscopy is yet to be employed in studies of mandibular kinematics.

The use of video x-ray fluoroscopy in measurement of mandibular and TMJ kinematics has been adopted primarily in the research setting due to the specialised software and computation time required for image processing. The total radiation dose for a 10 second single-plane fluoroscopy recording is approximately 135 μSv, about 15% of the acceptable annual dose suggested by the United States Nuclear Regulatory Commission (USNRC) (Chen et al., 2013a). The image capture rate can be as low as 7.5 frames per second, which may limit the fidelity of mandibular motion measurements, particularly during dynamic mastication.

Four-dimensional computed tomography (CT)

Four-dimensional computed tomography (4D CT) can be used to directly measure mandibular kinematics by digitally reconstructing geometric data obtained from 4D CT image sequences. Originally used for surgical planning, 4D CT was first employed in the measurement of wrist kinematics in 2011 (Leng et al., 2011), and has since been adopted to assess mandibular motion during mastication after mandibular reconstruction surgery (Akashi et al., 2016) and in TMJ osteoarthritis patients (Akashi et al., 2018). While 4D CT is seldom applied in mandibular or TMJ kinematics measurement, it has potential to be the 'gold standard' measurement technique, since it avoids errors associated with skin-motion artefact, transoral device motion and bone coordinate registration errors. While the accuracy of 4D CT has not been reported for mandibular kinematics, a study of wrist motion reported errors in the range 0.02-0.30 mm for translation and 0.00-0.68° for rotation (Zhao et al., 2015). The application of 4D CT in the clinical setting has been primarily limited by the radiation dosage. For a 10-15 second scan with a field of view of 220 mm and a frame rate of 7.5 frames per second, the effective radiation dose has been reported at 3.58 ± 0.88 mSv (Akashi et al., 2016), about 350% of the acceptable annual dose suggested by the USNRC. Restricted frame rate, limited field of view, and significant image processing time for kinematics measurement are other major drawbacks of this technique.

DISCUSSION

Mandibular kinematics have played an important role in evaluating internal muscle and joint forces (Rohrle and Pullan, 2007), improving TMJ prosthesis design (Ackland et al., 2017) and assessing occlusal loading (Röhrle et al., 2018). Measurement of mandibular kinematics in the clinical setting, which typically requires rapid data collection, ease of use and minimal invasiveness, is most commonly performed using mechanical linkage systems such as axiography and ultrasonic position monitoring. Commercial ultrasonic tracking equipment is gaining popularity over axiography, as it is faster and simpler to deploy, requires less calibration, and employs lightweight face-bows that do not impede natural mandibular motion. Research applications, which tend to favour accuracy over measurement and data processing time, have traditionally favoured electromagnetic and optoelectronic tracking systems; however, recent advances in miniature magnetic sensor design have facilitated both rapid and accurate acquisition of mandibular kinematics and may be suitable as a tool in the clinical settings.

Quantification of TMJ kinematics cannot ordinarily be performed using mandibular motion data alone, and condyle positions must be determined relative to those of the skull. Axiography, the Case Gnathic Replicator, ultrasonic, electromagnetic and optoelectronic tracking all rely on either kinematically determined approximations of condyle location (a fixed joint centre-of-rotation), or approximations of condyle position based on the digitisation of palpated landmarks. This is typically achieved by identifying a landmark on the anatomic condyle; however, this point may differ from the actual joint centre of rotation by between 4.5mm and 10 mm (Gallo et al., 2008, 1997). For accurate approximations of condyle location using these systems, motion tracking data must be registered to 3D mandibular anatomy, which can be achieved using medical imaging such as MRI or CT, but this can be a highly time-consuming computational process. While radiographic tracking such as video x-ray fluoroscopy or 4D CT provide direct measures of mandible or TMJ motion, the image processing and data analysis required is non-trivial, and the ionising radiation may present an ethical dilemma.

Optoelectronic tracking systems are capable of recording 3D mandibular motion non-invasively; however, motion tracking of the face using markers placed on the skin is likely to introduce significant skin motion artefact, particularly for larger mouth opening. Skin motion artefact can be overcome by attaching tracking markers directly to dental splints; however, splint manufacture can be time consuming, and requires specialist expertise and equipment for fabrication on a subject-specific basis. Markers may also be directly attached to the teeth, but it can be challenging to accurately register marker positions to jaw morphological data, and this approach is rarely performed. In general, optoelectronic tracking systems require the use of a multi-camera system with a large footprint, and extensive post-capture data processing. While less conducive to the clinical setting, this review reported these systems to be of high precision and reliability, and are considered the standard in non-invasive joint kinematics measurement for human movement studies.

Sophisticated magnetic tracking systems such as the Dental Motion Decoder (DMD) (Ignident, Ludwigshafen) overcome the size and cost constraints of optoelectronic systems through the use of small magnetic sensors directly to the teeth (Figure 10A), eliminating the requirement for custom dental splints. A handheld intraoral scanner can be employed to digitise both the sensor and dental topology simultaneousky (Figure 10B), which enables registration of motion data to 3D geometry of the dental arches. Following registration, mandibular motion can then be recorded in six degrees-of-freedom during dynamic activities including chewing (Figure 10C). While in their infancy, these systems show future promise as a clinical tool for mandibular motion analysis due to the potential for fast and accurate non-invasive data collection in a confined space; however, TMJ motion analysis may still be challenging due to the limited capacity of this system to accurately locate the mandibular condyle, or quantify TMJ centre of rotation.

Measurement of accurate mandibular kinematics has directly facilitated estimation of occlusal and mandibular loading during static and dynamic tasks. For example, 3D subject-specific bite force and occlusal pressure distributions have been estimated by driving finite element model simulations of dynamic chewing on a rubber sample with mandibular motion data acquired from optoelectronic tracking (Röhrle et al., 2018). This modelling approach overcomes the practical limitations of employing conventional uniaxial bite force transducers i.e. biting down on a metal sensor, which may be difficult and uncomfortable for a subject, and provides 3D bite force data, including shear loading at the occlusal surface; however, such an approach requires highly accurate mandibular kinematics: Our calculations have shown that a jaw kinematics error of just 0.21 mm may lead to a discrepancy in bite force of approximately 40 N. Combining high precision motion data with computational simulations also has broad application in evaluating muscle and joint function. Muscle forces during activities of daily living can be calculated using musculoskeletal models and motion data by solving the static indeterminacy problem i.e. that there are more muscle-tendon actuators than degrees of freedom of TMJ motion, prohibiting calculation of a unique muscle force solution. This has been achieved using optimisation-based methods and EMG-driven modelling approaches (Rohrle and Pullan, 2007; Sagl et al., 2019). Finite element models of the entire jaw complex that combine kinematics and muscle-tendon loading have subsequently been used to evaluate bone stress and strain (Koolstra and Van Eijden, 2005), and have had application in design and evaluation of TMJ prostheses (Ackland et al., 2017, 2015).

In conclusion, axiography and ultrasonic tracking provide fast and cost-effective mandibular motion measurements for use in the clinical setting; however, these methods are associated with greater measurement errors and the required hardware may have potential to hinder natural mandibular movement. Optoelectronic tracking generates accurate and robust motion analysis data but is expensive, requires a large, dedicated laboratory space, and necessitates fabrication of person-specific dental splints to overcome skin motion artefact. Radiographic methods such as video x-ray fluoroscopy and 4D CT provide direct measures of mandibular motion but are associated with significant radiation exposure and data processing time. Miniature magnetic tracking sensors that can be quickly adhered to teeth, combined with intra-oral scanning, shows promise in providing unobtrusive, rapid and accurate measurements of mandibular motion in both the clinic and research setting.

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FIGURE CAPTIONS

Figure 1: Flow chart illustrating systematic review search results adopted in the present study.

Figure 2: Quality assessment results for studies included in this systematic review including (A) the average score for each question in the quality assessment tool, and (B) the distribution of total quality scores, where high methodological quality is defined as a score of ≥ 20, moderate quality is defined as a score of > 14 and < 20, and low quality is defined as a score of ≤ 14. Red bars indicate questions that were poorly addressed (i.e. an average score of < 1.3).

Figure 3: The Case Gnathic Replicator, with two face-bows attached to the mandibular and maxillary teeth, transducers are mounted to the face-bows with connecting wires for making recordings of transducer displacements. Indicated with a black arrow

is one of six transducers used to characterise motion of the mandible (Messerman, 1967).

Figure 4: Electromechanical axiograph mounted to patient's mandible using an occlusal clutch, and attached to the forehead via a headband. The sensors are positioned in line with the hinge axis and their positions relative to the stationary maxillary flaps are recorded in the X (sagittal), Y (transversal) and Z (vertical) directions (Sadat-Khonsari et al., 2003a).

Figure 5: Ultrasonic tracking system used to measure relative displacement of the mandible to the skull, with three ultrasonic emitters mounted to the lower teeth via a metal clutch, and four ultrasonic receivers mounted on the head via a face-bow (Baqaien et al., 2007).

Figure 6: Magnetic tracking system used for quantifying condylar trajectories. A) custom plastic dental stents embedded with metal beads to enable motion data to be registered to CT scans, magnetic sensors are attached to the stents over the incisors, note the locations of the metal beads. B) Diagram of magnetic tracking system during recording sessions, magnetic sensors are attached to dental stents, their positions and orientations are calculated with respect to a magnetic source placed posterior to the subjects head (Baltali et al., 2008b).

Figure 7: Schematic of an Optoelectronic tracking system. Lightweight frames, each containing three pairs of photocells are attached to the upper and lower incisors and canines, while two perpendicular cathode ray tubes displays the movements

of these photocells, which can be reconstructed to evaluate 3D marker trajectories (Visscher et al., 2000).

Figure 8: 3D Scanning with adhesive targets attached to the teeth. Real-time CBCT scan and digital reconstructions are shown for (a) initial opening (b) partial jaw opening (c) right lateral movement and (d) left lateral movement (Kwon et al., 2019).

Figure 9: Photograph of a cone beam CT system with custom-made video x-ray fluoroscopy function for radiographic evaluation of dynamic TMJ kinematics. The participants head is fixed to a head-support with a head strap to stabilise the motion, while the participant wears a lead apron to minimise radiation absorption elsewhere in the body (Chen et al., 2013b).

Figure 10: Magnetic Dental Motion Decoder (DMD) system with magnetic sensors fixed to participant's premolars using dental cement (A). The motion of these sensors can be registered to subject-specific dental geometry reconstructed from an intra-oral scanner (B), resulting in three orthogonal translations and rotations of the mandible with respect to the maxilla during habitual mastication (C). Data given are expressed about an anatomic coordinate system with the x-direction, y-direction and z-direction aligned with the lateral, anterior and superior directions, respectively.

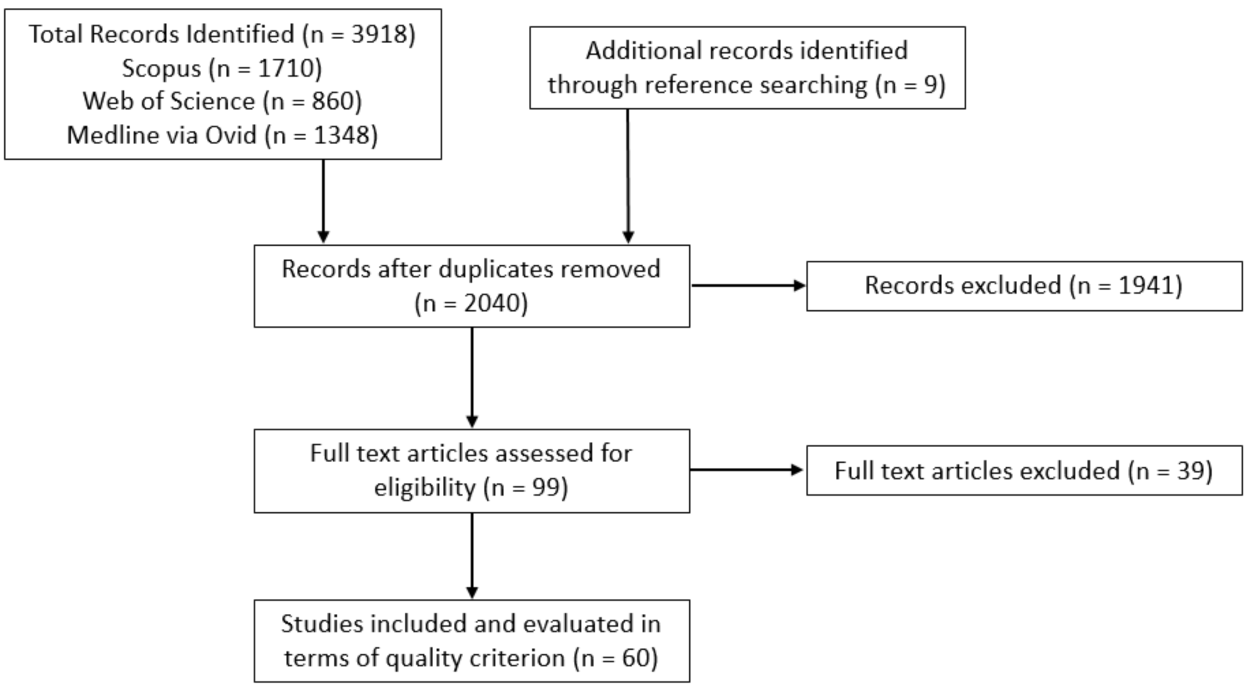
TABLE CAPTIONS

Table 1: Quality Assessment Tool employed in this Systematic Review. The scoring system was derived developed the STROBE statement (Elm et al., 2007), the Downs and Black checklist (Downs and Black, 1998), and previously reported reliability and feasibility appraisal tools (Crowe and Sheppard, 2011).

Table 2: Details of included studies using 3D Scanning, Axiography, Case Gnathic Replicator, Magnetic Tracking, Video X-Ray Fluoroscopy and Ultrasonic Tracking including use of medical imaging, kinematic parameters measured, study quality rating and authors.

Table 3: Details of included studies using Optoelectronic Tracking including use of medical imaging, kinematic parameters measured, study quality rating and authors.

Figure 1



Total Records Identified (n = 3918)
Scopus (n = 1710)
Web of Science (n = 860)
Medline via Ovid (n = 1348)
Additional records identified through reference searching (n = 9)
Records after duplicates removed (n = 2040)
Records excluded (n = 1941)
Full text articles assessed for eligibility (n = 99)
Full text articles excluded (n = 39)
Studies included and evaluated in terms of quality criterion (n = 60)

Figure 2

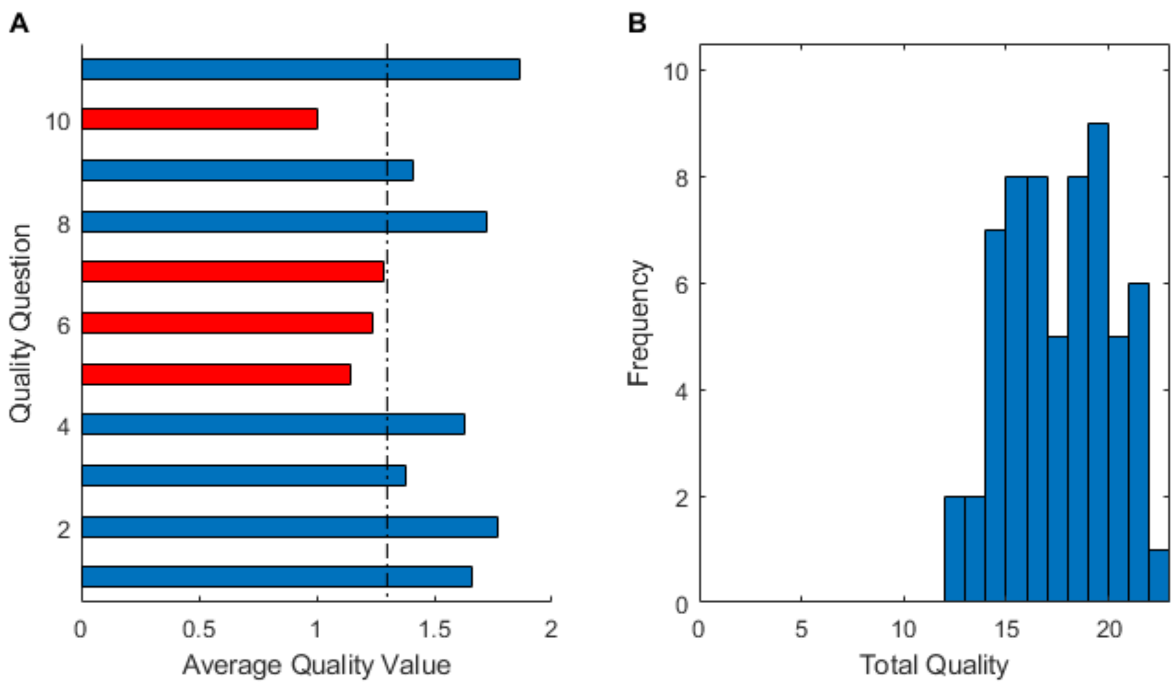

A
Quality Question
Average Quality Value
B
Frequency
Total Quality

Figure 3

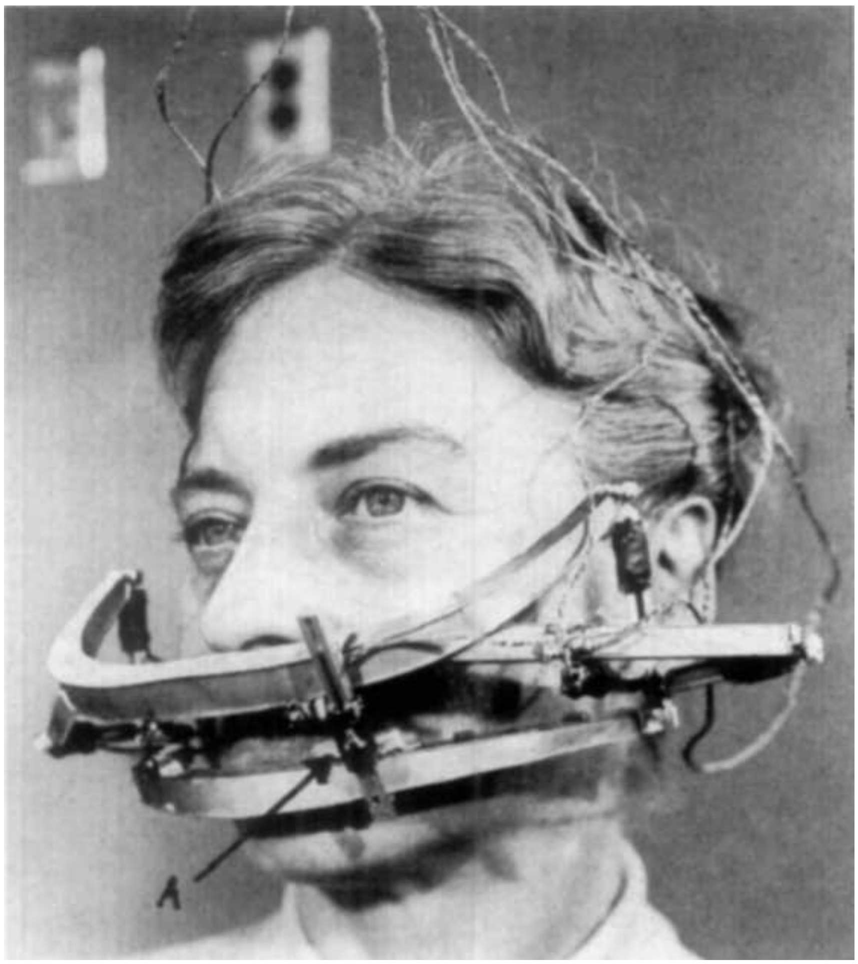


Figure 4

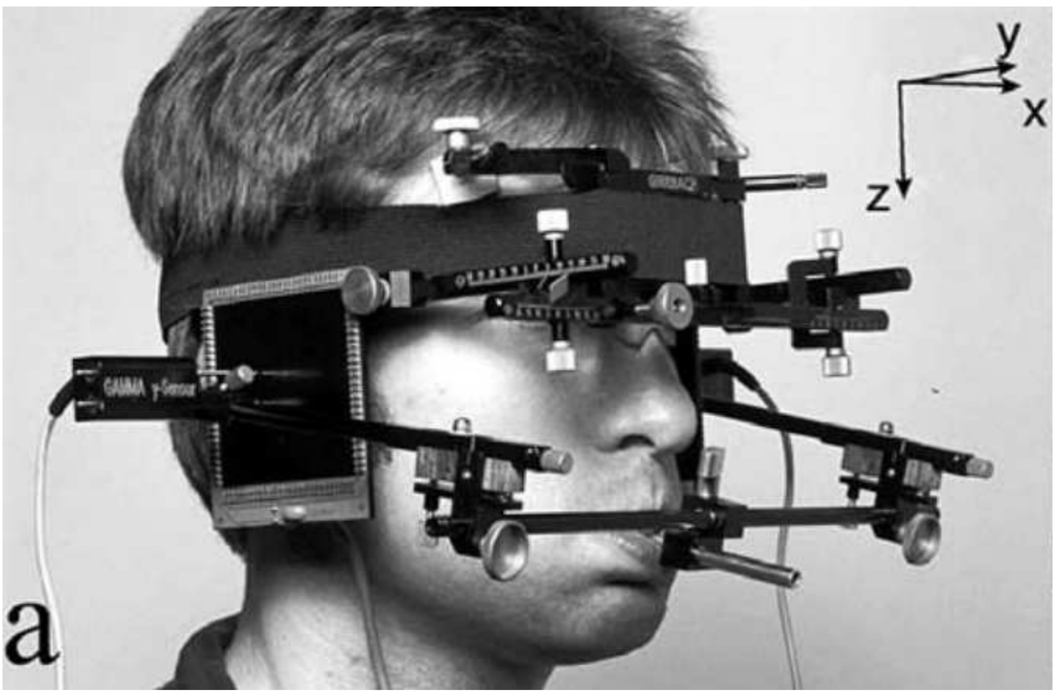


Figure 5

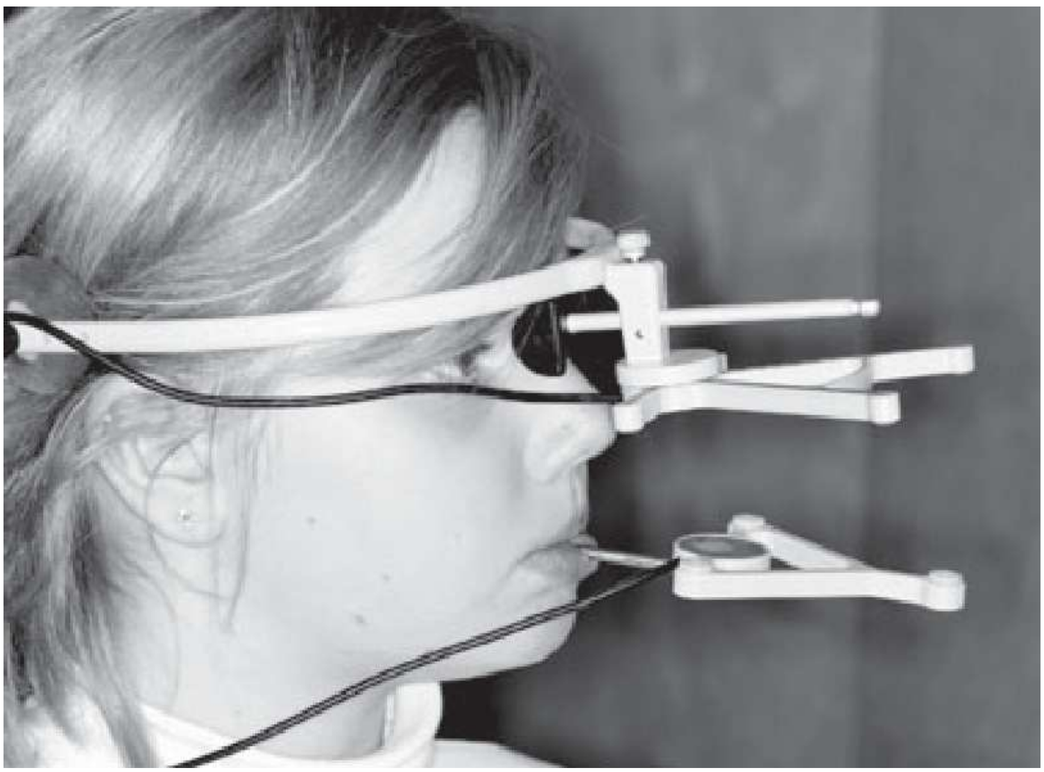


Figure 6

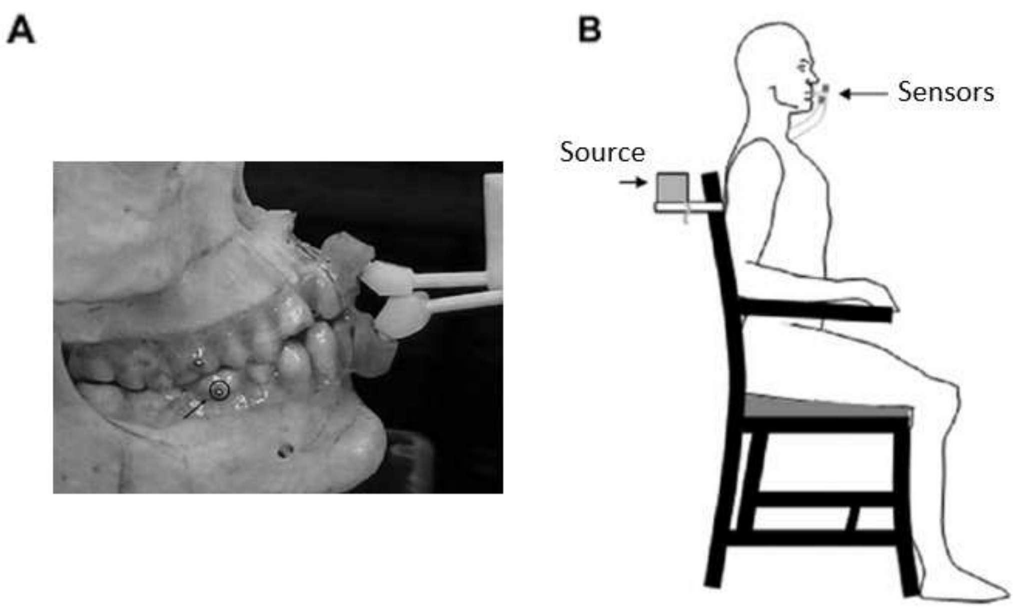


Figure 7

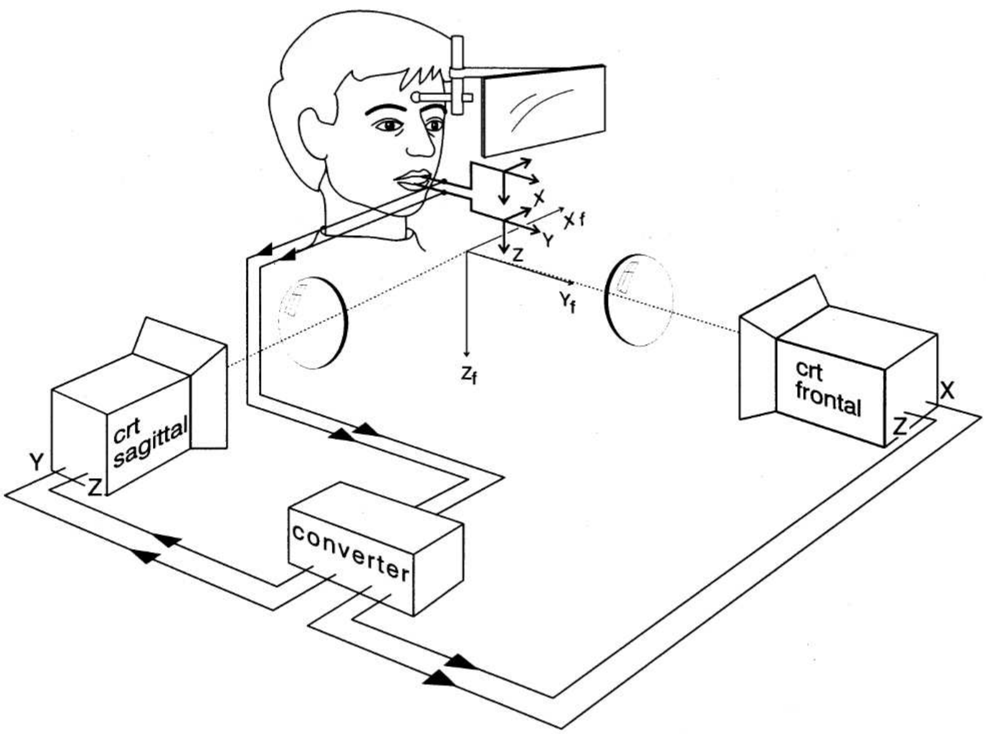


Figure 8

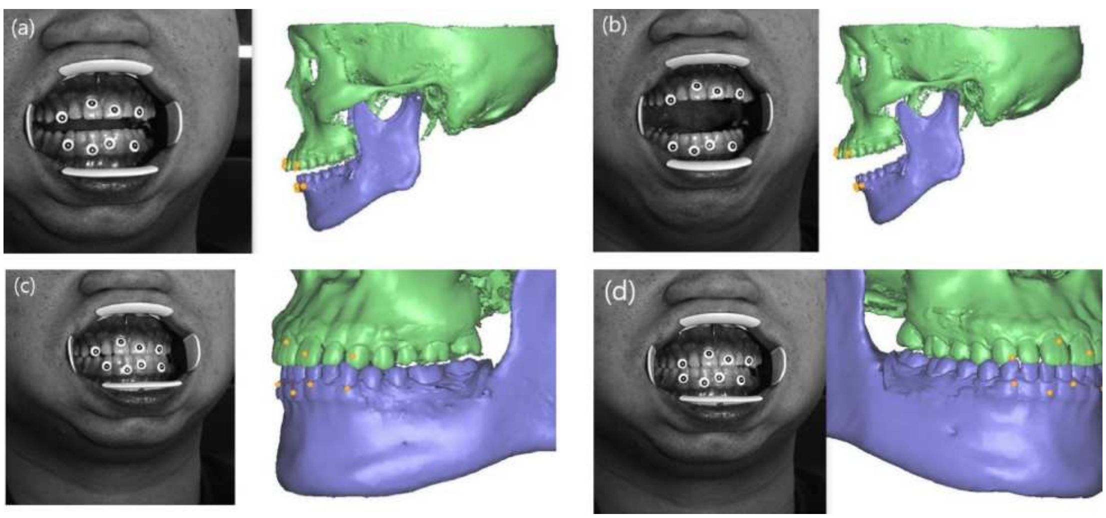


Figure 9

Figure 10

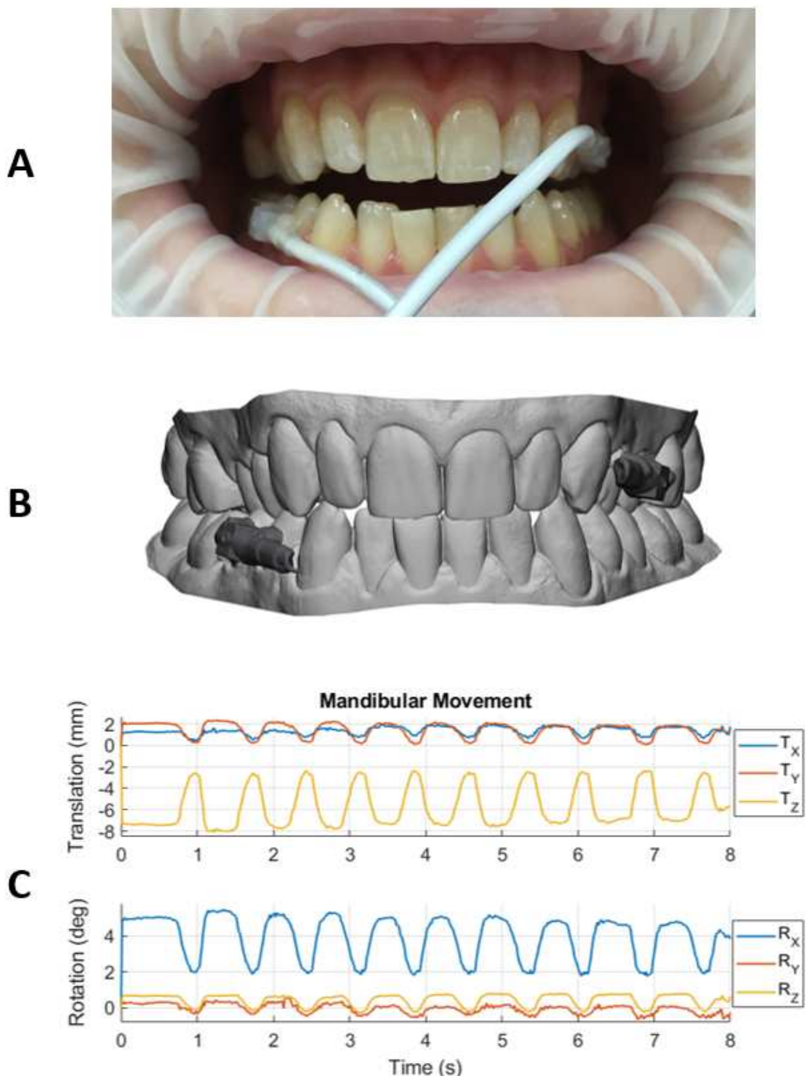

A
B
C
Mandibular Movement
Translation (mm)
2
0
-2
-4
-6
-8
0 1 2 3 4 5 6 7 8
T_X
T_Y
T_Z
Rotation (deg)
4
2
0
0 1 2 3 4 5 6 7 8
Time (s)
R_X
R_Y
R_Z

Table 1: Quality assessment tool employed in this Systematic Review. The scoring system was derived from the STROBE statement (Elm et al., 2007), the Downs and Black checklist (Downs and Black, 1998), and previously reported reliability and feasibility appraisal tools (Crowe and Sheppard, 2011).

	Assessment of Quality
1	Is the scientific background and rationale for the study clearly described?
2	Are the research objectives or aims clearly stated?
3	Are the precise details of the measurement system design and setup described?
4	Are the parameters to be measured clearly stated?
5	Is the selection of participants and controls clearly described?
6	Is participant inclusion and exclusion criteria clearly stated?
7	Is the equipment to participant attachment method clearly described?
8	Where relevant, is the registration system between anatomy and motion measurements clearly described?
9	Are participant movement tasks clearly defined?
10	Was there a discussion of the errors introduced in the preparation/measurement system/data handling?
11	Are the main outcomes of the study clearly stated?

Table 2: Details of studies in this Systematic Review that employed 3D Scanning, Axiography, Case Gnathic Replicator, Magnetic Tracking, Video X-Ray Fluoroscopy and Ultrasonic Tracking. Included are use of medical imaging, kinematic parameters measured and study quality rating.

Technique	Sample Size	Imaging	Kinematic Parameters	Quality Rating	Authors
3D scanning	1	CT	Kinematic Hinge Axis	15	Kwon et al., 2019
Axiography	22	-	Condylar Trajectories	17	Alsawaf et al., 1993
Axiography	60	-	Condylar Trajectories	18	Hüe et al., 2011
Axiography	50	-	Kinematic Hinge Axis	16	Sadat-Khonsari et al., 2003a
Axiography	8	-	Helical Axis Trajectory	15	Sadat-Khonsari et al., 2003b
Axiography	49	-	Condylar Trajectories	15	Theusner et al., 1993
Case Gnathic Replicator	8	-	Condylar Trajectories	20	Coffey et al., 1989
Case Gnathic Replicator	12	-	Condylar & Incisal Trajectories	17	Gibbs et al., 1971
Magnetic Tracking	12	-	Condylar & Helical Axis Trajectories	15	Baeyens et al., 2013
Magnetic Tracking	5	CT	Condylar & Incisal Trajectories	20	Baltali et al., 2008b
Magnetic tracking	14	CT	Condylar, Incisal & Helical Axis Trajectories	19	Baltali et al., 2008a
Magnetic Tracking	36	CT	Condylar, Incisal & Helical Axis Trajectories	13	Keller et al., 2012
Ultrasonic Tracking	223	-	Condylar Inclination Angle	18	Baqaien et al., 2007
Ultrasonic Tracking	35	CT	Condylar Trajectories	18	Kiseri et al., 2018
Ultrasonic Tracking	21	-	Condylar & Incisal Trajectories	14	Ko et al., 2015
Ultrasonic Tracking	259	-	Condylar Trajectories	14	Kordaß et al., 2014
Ultrasonic Tracking	36	-	Condylar, Incisal and Helical Axis Trajectories	19	Linsen et al., 2016
Ultrasonic Tracking	60	-	Condylar Trajectories & Kinematic Hinge Axis	16	Morneburg et al., 1998
Ultrasonic Tracking	23	-	Kinematic Hinge Axis & Condylar Inclination Angles	12	Ratzmann et al., 2007
Ultrasonic Tracking	44	-	Condylar Trajectories	14	Wang et al., 2009
Video X-Ray Fluoroscopy	1	CT	Condylar Rotations & Translations	16	Chen et al., 2013a
Video X-Ray Fluoroscopy	1	CT	Kinematic Hinge Axis	18	Chen et al., 2013b
Video X-Ray Fluoroscopy	1	CT	Condylar Rotations & Translations	13	Yamazaki et al., 2014

Table 3: Details of studies in this Systematic Review that employed Optoelectronic Tracking, including their use of medical imaging, kinematic parameters measured, and study quality rating.

Sample Size	Imaging	Kinematic Parameters	Quality Rating	Authors
26	-	Incisal Trajectories and Mastication Cycle Data	21	Buschang et al., 2000
27	-	Condylar & Incisal Trajectories	20	Buschang et al., 2001
26	CT	Intra-Articular Joint Space	18	Chang et al., 2015
32	-	Condylar Rotations & Translations	14	Coutant et al., 2008
20	MRI	Condylar Trajectories & Intra-Articular Joint Space	16	Ettlin et al., 2008
27	-	Incisal Trajectories	21	Ferrario et al., 2005
10	MRI	Intra-Articular Joint Space	21	Fushima et al., 2003
30	-	Helical Axis Trajectory	21	Gallo et al., 1997
7	-	Helical Axis Trajectory	19	Gallo et al., 2000
50	-	Helical Axis Trajectory	21	Gallo et al., 2006
11	MRI	Condylar Trajectories & Intra-Articular Joint Space	16	Gallo et al., 2008
15	CT	Condylar Trajectories	14	Kim et al., 2010
5	MRI	Condylar Trajectories & Intra-Articular Joint Space	22	Krebs et al., 1994
1	MRI	Intra-Articular Joint Space	20	Krebs et al., 1995
6	MRI	Condylar Trajectories	18	Leader et al., 2003
1	MRI	Condylar & Incisal Trajectories	15	Leiggener et al., 2012
10	-	Mandibular Centre of Rotation	17	Lemoine et al., 2005
56	-	Kinematic Hinge Axis & Incisal Trajectories	19	Lewis et al., 2001
26	-	Condylar Trajectories	19	Mapelli et al., 2009
40	-	Condylar & Incisal Trajectories	18	Mapelli et al., 2016
10	-	Condylar Trajectories	14	Naeije and Hofman, 2003
35	-	Condylar Rotations & Translations	16	Naeije, 2002
4	-	Kinematic Hinge Axis	15	Ostry et al., 1997
1	CT	Kinematic Hinge Axis & Intra-Articular Joint Space	15	Otake et al., 2006
58	-	Kinematic Hinge Axis	15	Sforza et al., 2010
46	-	Incisal Trajectories	20	Sforza et al., 2011
3	-	Condylar Trajectories	17	Siegler et al., 1991
10	-	Condylar Trajectories	19	Slater et al., 1999
1	CT	Intra-Articular Joint Space & Oclusal Contact Area	17	Terajima et al., 2008
18	-	Condylar & Incisal Trajectories	19	Ugolini et al., 2017
10	-	Condylar & Incisal Trajectories	18	Visscher et al., 2000
5	MRI	Condylar Trajectories	12	Wojczynska et al., 2019
10	MRI	Condylar Trajectories & Intra-Articular Joint Space	14	Yashiro et al., 2015b
20	CT/MRI	Condylar Trajectories & Intra-Articular Joint Space	16	Yashiro et al., 2015a
20	-	Condylar Trajectories	19	Yatabe et al., 1995
20	-	Condylar Trajectories	19	Yatabe et al., 1997
6	MRI	Condylar Trajectories & Intra-Articular Stress-Fields	21	Zaugg et al., 2012